Comparative Study of a Zircaloy-based Fuel and Accident Tolerant Fuel for a Design Basis Accident Analysis

Ju Yeop Park [a*], Yongsik Yang [b], Changhwan Shin [b]
[a]*Korea Institute of Nuclear Safety, Safety Analysis Dept., 62 Gwahak-ro, Yuseong-gu, Daejeon 34142*
[b]*Korea Atomic Energy Research Institute, 111 Daedeok-daero 989 Beon-gil, Yuseong-gu, Daejeon 34057*
[*]Corresponding author: k385pjy@kins.re.kr

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1. Introduction

Nuclear industry in Korea has been working on developing Accident Tolerant Fuel (ATF) since 2022 aiming at commercial loading of ATFs into reactors in 2034. The ATF currently under being developed is a short-term ATF and it employs chromium coating on zircaloy alloy cladding. A major target of the ATF is to reduce runaway exothermic reaction with hot steam producing hydrogen and as a result, to delay or prevent hydrogen explosion inside a crippled reactor when a severe accident happens. On top of that, ATF also has another target to show a better performance during normal operation, Anticipated Operational Occurrences (AOOs) and Design Basis Accidents (DBAs) in terms of safety margin compared to conventional fuels. This is the motivation of the present study. In the present paper, comparative MARS-KS code analysis results between a zircaloy-based fuel and ATF with chromium coating for a DBA (Large-Break Loss of Coolant Accident; LB LOCA) conducted through KINS regulatory safety research on ATF are summarized. Specifically, Peak Cladding Temperature (PCT) during LB LOCA is focused to see if the introduction of ATF could bring higher safety margin from LB LOCA PCT perspective.

2. Thermal-Hydraulic System Code Update for ATF

In order to analysis LB LOCA with ATF by MARS-KS code, some parts of the code should be modified reflecting thermo-mechanical properties of chromium coated zircaloy cladding. In the following subsections, updates conducted on MARS-KS code are summarized

2.1 Metal-Water Reaction Model

Both of zircaloy and chromium have different exothermic high temperature oxidation reactions mechanism. Since only zircaloy based high temperature oxidation reaction is included in the original MARS-KS code (See MARS-KS(Zr) in Fig.1), chromium based high temperature oxidation reaction was implemented in MARS-KS code as an update. Since chromium metal-water reaction varies depending on coating process, minor impurities in the coating, and post process after coating, Brachet et al. chromium metal-water reactor model [2] is employed in the present study.

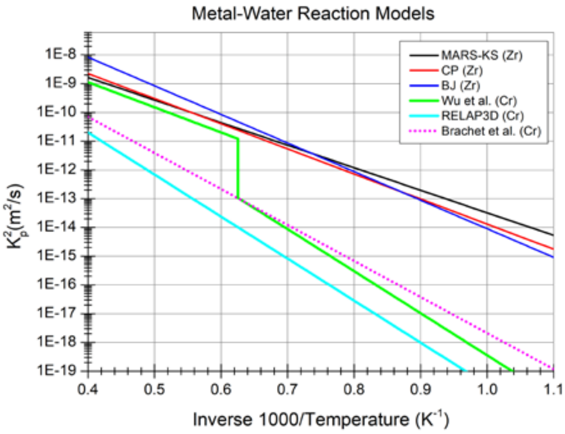

Fig. 1. Various metal-water reaction models for zircaloy or chromium [1].

2.2 Cladding Deformation Model

MARS-KS code adopts zircaloy cladding deformation model based on NUREG-0630. The cladding deformation model provides additional modification to the gap conductance by adding radiation heat transfer between fuel pellet and deformed cladding. The purpose of the model is to allow plastic deformation (including creep deformation) of the cladding to be accounted for in the calculation of fuel rod's cladding temperature during LOCA simulations. Therefore, it is required to update the original cladding deformation model for chromium coated zircaloy cladding in a strict sense. However, it is common practice not to implement the cladding deformation model during LOCA calculation because lower gap conductance (i.e. without the radiation heat transfer from the deformation model) usually leads to higher PCT. Therefore, the zircaloy based cladding deformation model is not updated for the chromium coated zircaloy cladding and the model option turns off in the present study from conservative PCT point of view.

2.3 Thermal Property: Heat Conductivity

In the present study, the original MARS-KS heat structure model for fuel rod is maintained. Therefore, in order to implement chromium coating effect on existing MARS-KS heat structure which is composed of pellet, gap and zircaloy cladding, an equivalent cladding concept should be introduced. That is to say, heat conductivity, one of zircaloy cladding thermal properties is modified considering chromium coating effect on zircaloy substrate. It is assumed that zircaloy and chromium are mixed homogeneously and that equivalent heat conductivity is determined by mass weighting method. [3] Specifically, an equivalent heat conductivity of zircaloy cladding having 15 μm thick chromium coating is determined as below.

$$\begin{aligned} k_{equiv} &= \frac{M_{zr}}{M_{total}} k_{zr} + \frac{M_{cr}}{M_{total}} k_{cr} \\ &= \frac{\rho_{zr} V_{zr}}{\rho_{equiv} V_{total}} k_{zr} + \frac{\rho_{cr} V_{cr}}{\rho_{equiv} V_{total}} k_{cr} \\ &= \frac{\rho_{zr}}{\rho_{equiv}} VF_{zr} k_{zr} + \frac{\rho_{cr}}{\rho_{equiv}} VF_{cr} k_{cr} \qquad (1) \end{aligned}$$

where $\rho_{zr} = 6.505 g/cm^3$, $\rho_{cr} = 7.19 g/cm^3$, $\rho_{equiv} = 6.523495 g/cm^3$, $VF_{zr}(Volume\ Fraction) = 0.972725058$, $VF_{cr} = 0.027274942$. Volume fractions of zircaloy and chromium are determined by the following fuel rod model in Fig. 2.(Outer radius of the zircaloy cladding: 4.75mm, inner radius of the zircaloy cladding: 4.18mm).

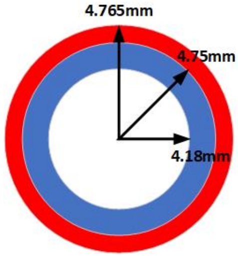

Fig.2 Fuel rod geometry

The resulting equivalent thermal conductivity is given by Fig.3

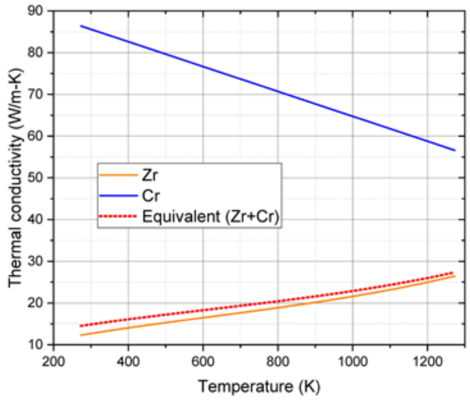

Fig.3 Thermal conductivities (Zr, Cr, Equivalent)

Here,

$$k_{cr}(W/m - ℃) = 86.4 - 0.0297 \times T(℃)\ [3] \qquad (2)$$

$$k_{zr}(W/m - K) = 7.511 + 2.088 \times 10^{-2} T(K) - 1.45 \times 10^{-5} T^2(K) + 7.668 \times 10^{-9} T^3(K)\ [4] \qquad (3)$$

2.4 Thermal Property: Heat Capacity

MARS-KS fuel rod heat structure requires cladding volumetric heat capacity input. Like the thermal conductivity, an equivalent heat capacity of chromium coated zircaloy cladding is applied for ATF. Since the volumetric heat capacity is given as multiplication between density and specific heat, equivalent density and equivalent specific heat are used to determine the equivalent volumetric heat capacity. Fig. 4 shows specific heat of zircaloy, chromium and chromium coated zircaloy(i.e. equivalent). Like the equivalent thermal conductivity, mass weighting method is applied to determine the equivalent specific heat.

$$c_{p,equiv} = \frac{M_{zr}}{M_{total}} c_{p,zr} + \frac{M_{cr}}{M_{total}} C_{p,cr} \qquad (4)$$

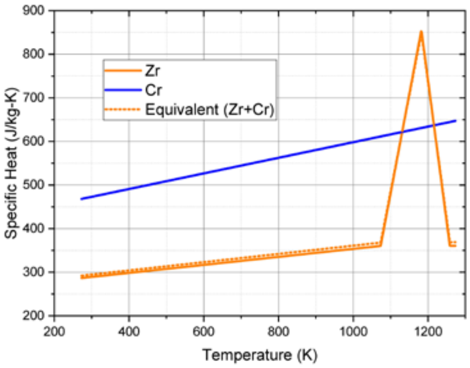

Fig.4 Specific heats (Zr, Cr, Equivalent)

The resulting equivalent heat capacity is given by multiplication between the equivalent density and the equivalent specific heat.

2.5 Mechanical Properties: Young's modulus and Yield stress

MARS-KS fuel rod heat structure model (i.e. gap conductance model, cladding deformation model) requires precise mechanical properties such as Young's modulus and yield stress in order to calculate elastic strain and to determine the entrance of plastic strain regime. Comparison of zircaloy cladding and chromium coated zircaloy cladding for stress-strain relationship shows that mechanical properties don't change much at low temperature. Otherwise, the change becomes bigger when temperature increases. This trend is due to the fact that For example, ATF cladding's yield stress and Young's modulus are increasing compared to zircaloy cladding as temperature increases and this is due to the fact that weakening of chromium strength is less than that of zircaloy. Since there are not many experimental data available so far, zircaloy mechanical properties apply to ATF cladding from conservative point of view.

3. Comparison of MARS-KS Code Calculations between zircaloy and ATF claddings

APR1400 LB LOCA simulations are conducted for conventional zircaloy cladding (zircaloy-4) fuel and ATF (chromium coated zircaloy-4 cladding) with the original MARS-KS code and the ATF modified MARS-KS code based on modification described in section 2, respectively. The nodalization adopted for these simulation is given in Fig. 5.

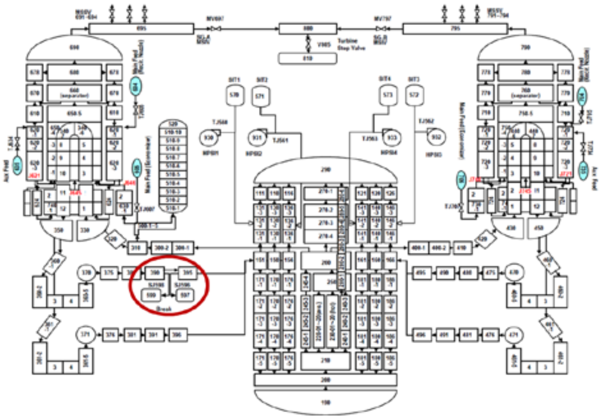

Fig.5 Nodalisation for APR1400 LB LOCA Analysis by MARS-KS Code

Fig.6 shows behavior of PCT between zircaloy-4 cladding fuel and ATF (chromium coated zircaloy-4 cladding). At the blowdown period, the blowdown PCT of ATF looks lower than that of the conventional zircaloy-4 cladding. This feature seems to be related to slight increase of equivalent thermal conductivity shown in Fig. 3 because high thermal conductivity contributes to reduction in pellet centerline temperature leading to lower initial stored energy during steady-state operation. It is well believed that initial stored energy in fuel rods contribute the blowdown PCT.

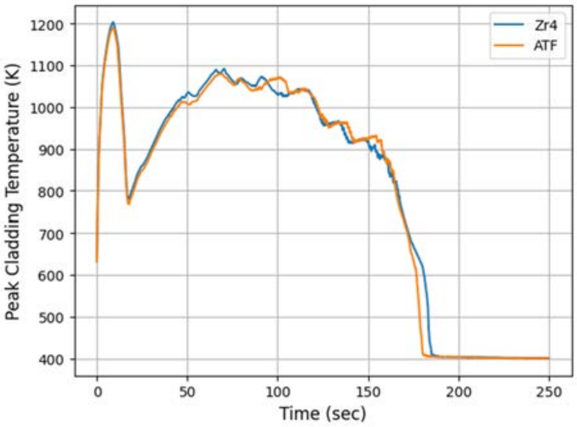

Fig.6 Nodalisation for APR1400 LB LOCA Analysis by

The very slight decrease of PCT during reflood period is observed for ATF over zircaloy fuel. Fig.6 shows the reflood PCT of ATF is almost comparable with that of the conventional zircaloy fuel. This phenomena in the reflood PCT seems to be due to the fact that the metal-water reaction model for chromium given in Fig. 1 does not play much during the reflood period. Although the metal-water reaction of chromium is much lower than zircaloy specially during the early stage of reflood period where cladding temperature remains high enough to produce active oxidation (up to 100sec in Fig.7), introducing ATF could not prohibit PCT increase during the early reflood period. This is the very interesting point because it has been usually assumed that ATF having high oxidation resistance may create lower PCT compared to conventional zircaloy cladding fuel. The present study shows unknow factor may play role in increasing PCT during the early stage of the reflood. The present study indicates that for ATF, the reduction of PCT in the blowdown period is obvious but PCT trend in the reflood period is quite uncertain.

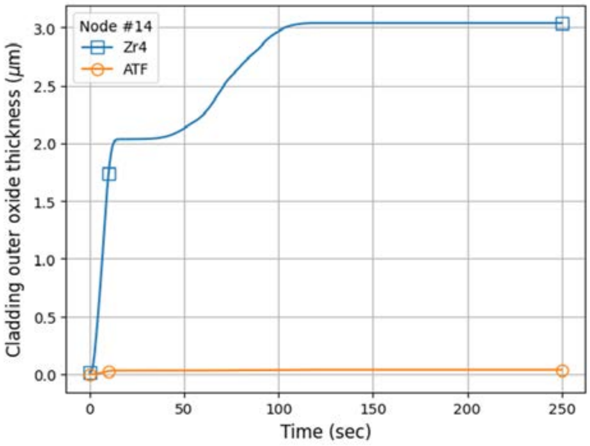

Fig.7 Cladding Oxide Thickness Growth of zircaly-4 and ATF

4. Conclusions

Comparative LB LOCA analysis of a zircaloy-based fuel and ATF with chromium coated zircaloy cladding is conducted for APR1400 by MARS-KS code. In order to analyze ATF, fuel rod heat structure models in MARS-KS is reviewed and updated when necessary. PCT trend of ATF and conventional zircaloy cladding fuel during the blowdown period well with the update of MARS-KS Code (thermal conductivity). But PCT trend for the reflood period is quite different from the anticipation. That is, the reflood peaks of ATF and conventional zircaloy cladding fuel are comparable each other although less metal-water reaction from chromium over zircaloy is implemented in MARS-KS code.

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